Bi-directional Wireless Power Flow for Medium-Duty Vehicle-to-Grid Connectivity

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2020 U.S DOE Vehicle Technologies Office Annual Merit Review
June 4th, 2020 Project ID: ELT188

ORNL is managed by UT-Battelle, LLC
for the US Department of Energy

Overview

Timeline
- Start – May 2017
- End – December 2020
- Budget Period I completed in May 2018
- Budget Period II Go/No-Go completed in Feb. 2020
- Project completion by Dec. 2020

Barriers
- 11 inches magnetic airgap for 20kW wireless power transfer (most applications are for 6-8 inches)
- Achieving bi-directional wireless power flow between grid and vehicle
- Achieving high-efficiency (≥85%) at 20kW with 11 inches airgap
- Meeting the grid and utility standards at the grid side while meeting power density and reliability targets

Budget
- Total project funding
  - DOE share – $1.95M
  - Cost share from partners – $712K
- Project spending BP1: $650K
- Project spending for BP2: $1.2M

Partners
- CALSTART (Project lead)
- ORNL (Technical lead), (Omer C. Onar, Gui-Jia Su, Jason Pries, Cliff White, Larry Seiber, Veda Galigekere, Randy Wiles, Jonathan Wilkins, Erdem Asa, Mostak Mohammad)
- UPS
- Workhorse
- Cisco

Project Objectives and Relevance

Overall Objectives:

- Design, model, simulate, build, integrate, and test a bi-directional wireless power transfer (BWPT) system for medium duty delivery trucks
  - A vehicle integrated ≥20 kW wireless power transfer system with bi-directional operation
  - High-efficiency (≥85%) with a nominal magnetic airgap of 11 inches
  - Vehicle-to-grid mode ≥6.6 kW wireless power transfer to building or grid loads (grid support or ancillary services)
  - Integration of the WPT system into the vehicle
  - Modeling and analysis of BWPT systems

FY 2020 Objectives:

- Complete the development of system power conversion stages
- Integrate auxiliary components (sensors, contactors, fuses, pre-charge circuitry, connectors, controllers, power supplies, etc.) and communication systems
- Test system power stages individually on laboratory benchtop setup
- Integrate the whole system together and validate functionalities
- Complete vehicle integrations and perform a vehicle integrated demonstration

Any proposed future work is subject to change based on funding levels

Project Milestones

Date	Milestones and Go/No-Go Decisions	Status
May 2018 **Budget Period I**	<u>Milestone:</u> Design, model, simulate, analyze system components. Determine system power architecture and control strategy for the BWPT system	Completed
February 2020 **Budget Period II**	<u>Milestone</u>: Develop (build) and test all the BWPT hardware for vehicle and grid sides, test all power conversion stages individually, complete benchtop tests, and integrate the system into the vehicle. Address the impact of BWPT on vehicle ESS, analyze the BWPT system benefits	Completed
December 2020 **Budget Period III**	<u>Milestone</u>: Full vehicle level testing and demonstration of the BWPT technology, deployment of the vehicle and system to the test site, perform operations, collect data	On-track

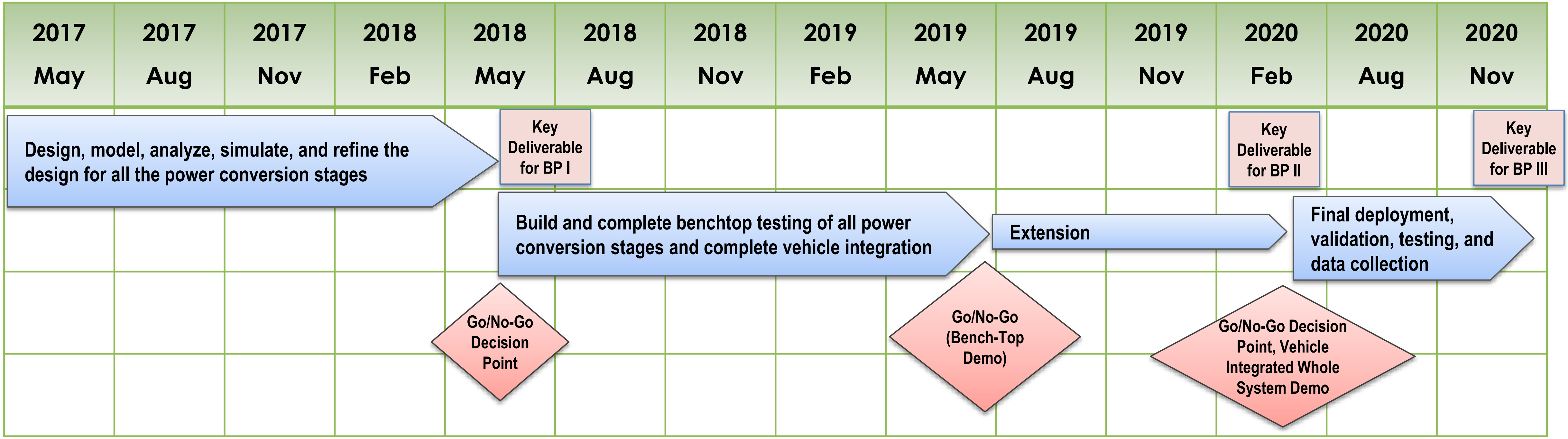
Any proposed future work is subject to change based on funding levels

Approach / Strategy

- Target operating conditions (power level, input grid voltage, vehicle battery voltage range, airgap, maximum current, etc.) are used for proper system level design and cascaded down to the appropriate subsystems and component designs
- Iterative design and the use of finite element analysis (FEA) based modeling for the design optimization of the electromagnetic coupling coils
- Build system power conversion stages in an integrated approach for an optimal system design in terms of complexity and compactness
- Validate that system components met the design parameters
- Test all the power conversion stages independently for functionality and validation of the performance
- Evaluate entire system using grid and battery emulators before vehicle integration
- Test and validate the integrated system on the test truck
- Site preparation and deployment for testing at the UPS facility and data collection

Any proposed future work is subject to change based on funding levels

Project Timeline



Go/No-Go Decision Points:

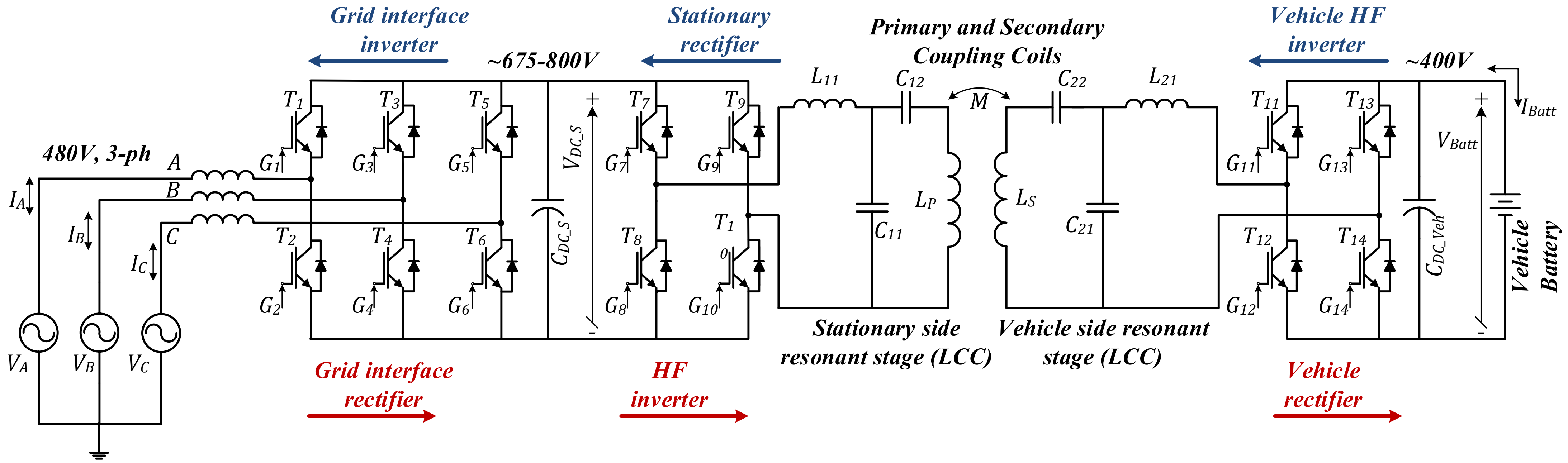
- Whether the system design and models indicate the feasibility of 20 kW wireless charging operation over 11 inches magnetic airgap with at least 85% efficiency (BPI)
- Limited objective (bench-top) demo with 20 kW operation for the bi-directional wireless power transfer system (BPII)
- **Vehicle integrated complete system demonstration in both power flow directions with all the targets met (BPII)**

Key Deliverable for BP III: Final deployment at the UPS SMART Hub facility, validation, demonstration, testing and data collection (~Dec. 2020)

Any proposed future work is subject to change based on funding levels

Technical Accomplishments – BP II

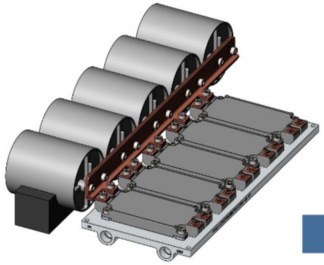
- Developed the hardware designed in BP-I.
- Modified the resonant tuning network to accommodate ~400V vehicle battery voltage due to the unavailability of all-electric truck with 650V battery voltage.
- Individually tested the power stage and tested parameters and functionality of each subsystems and components.
- May 2019 – demonstrated the dc-to-dc operation (without grid interface converter) with two dc emulators on each end.
- November 2019 – integrated the grid interface converter and started benchtop tests.
- February 2020 – completed vehicle integrations and verification of the system on the truck.



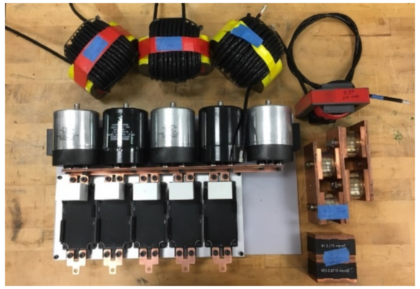
System level block diagram

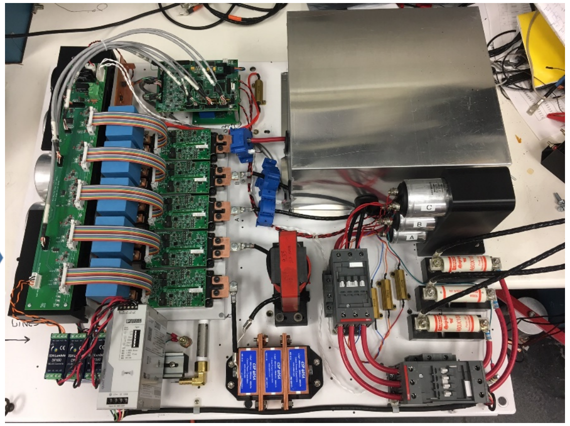
Technical Accomplishments – BP II

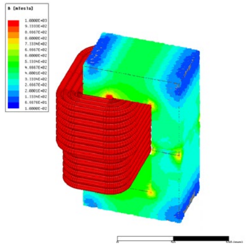
Power stage and resonant stage development



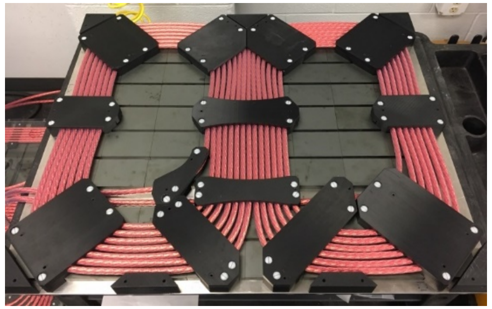
Primary-side power stage



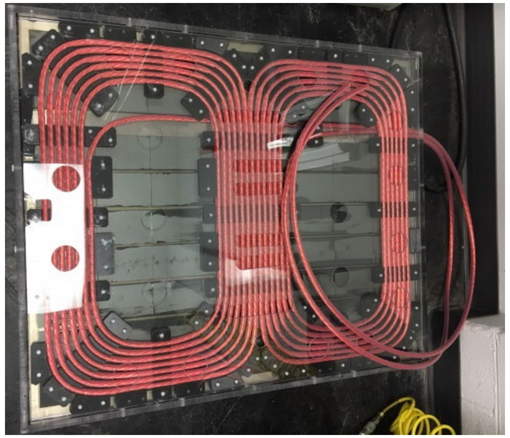




Grid interface inductors (3)

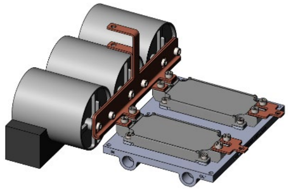


Primary coil

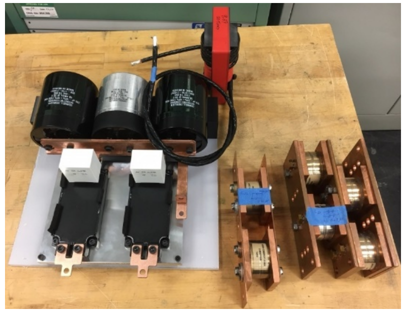


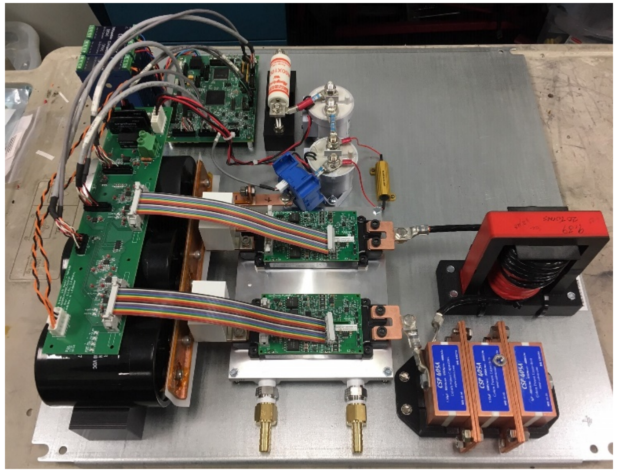
Secondary coil

May 2018 **October 2018** **March 2019**

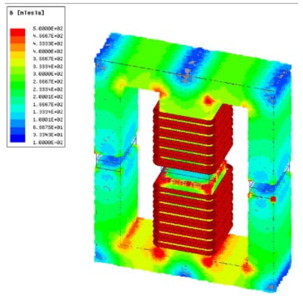


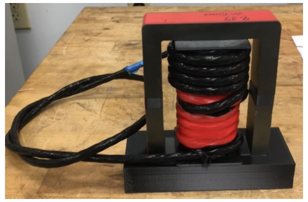
Secondary-side power stage



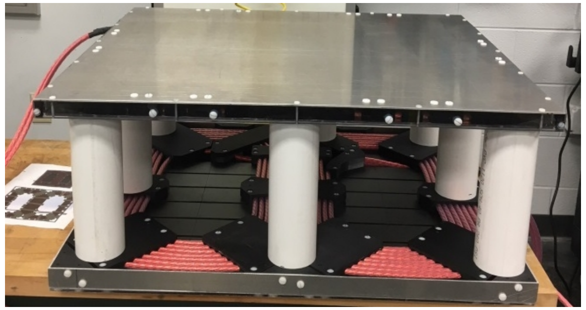


System hardware development progress





Primary and secondary side tuning inductors; design and physical build

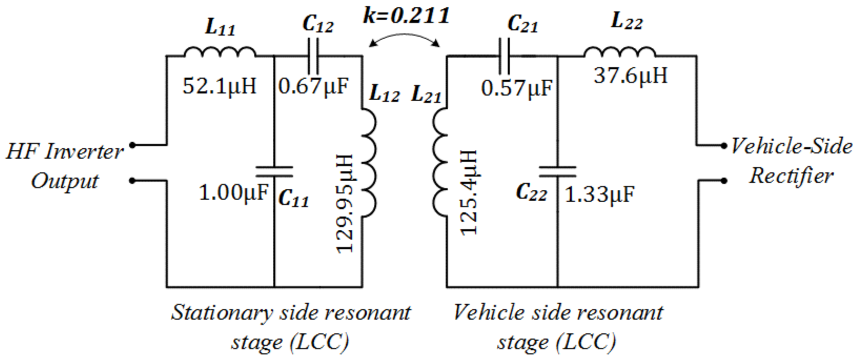


Coils with the required airgap

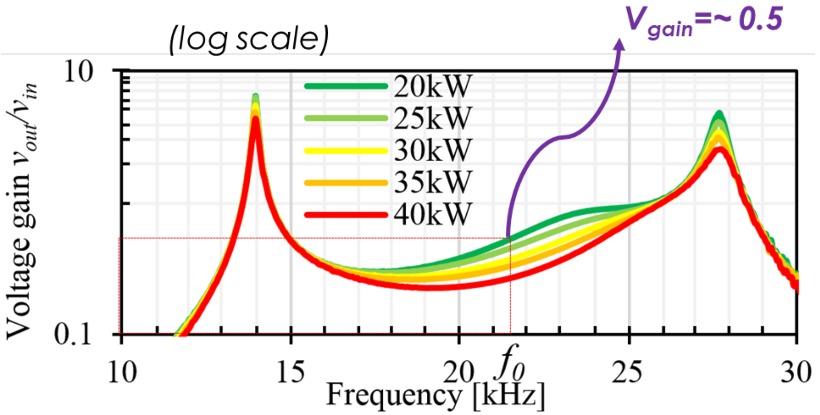
Technical Accomplishments – BP II

Performed voltage-gain analysis to validate the modifications

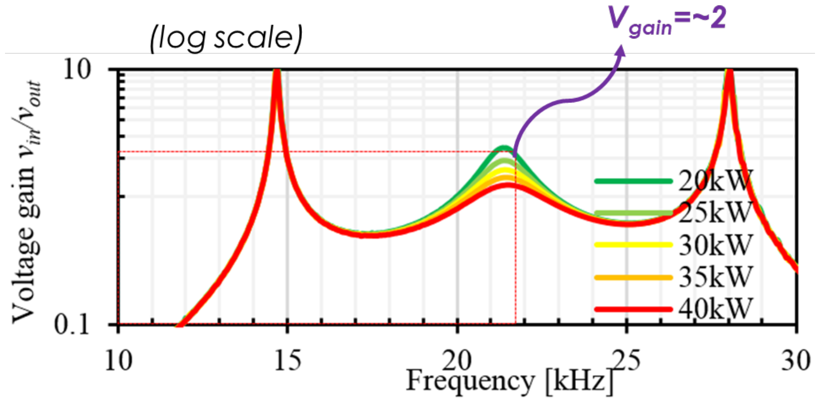
- ~800V bus to ~400V bus **(charging)**



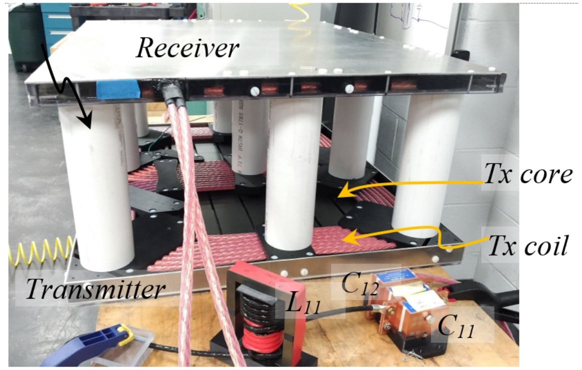
- ~400V bus to ~800V bus **(discharging)**
- Voltage gains are properly designed to reduce the control stress on the power devices
- Resonant gain provides most of the voltage conversion, power electronics only fine tunes the set points



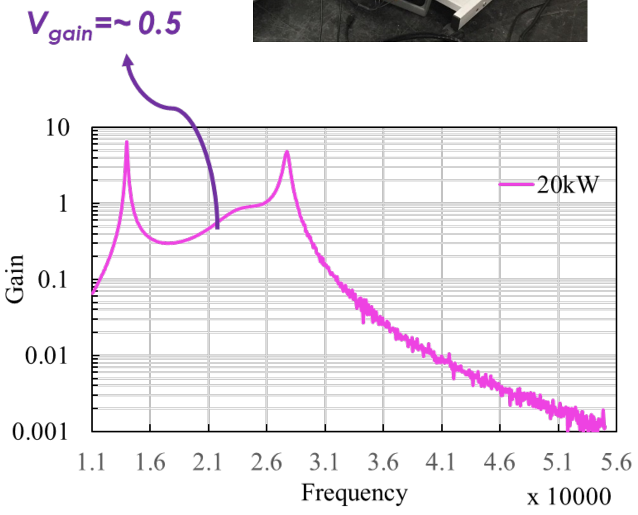
Voltage gain characteristic when charging the vehicle battery



Voltage gain characteristic when discharging the vehicle battery



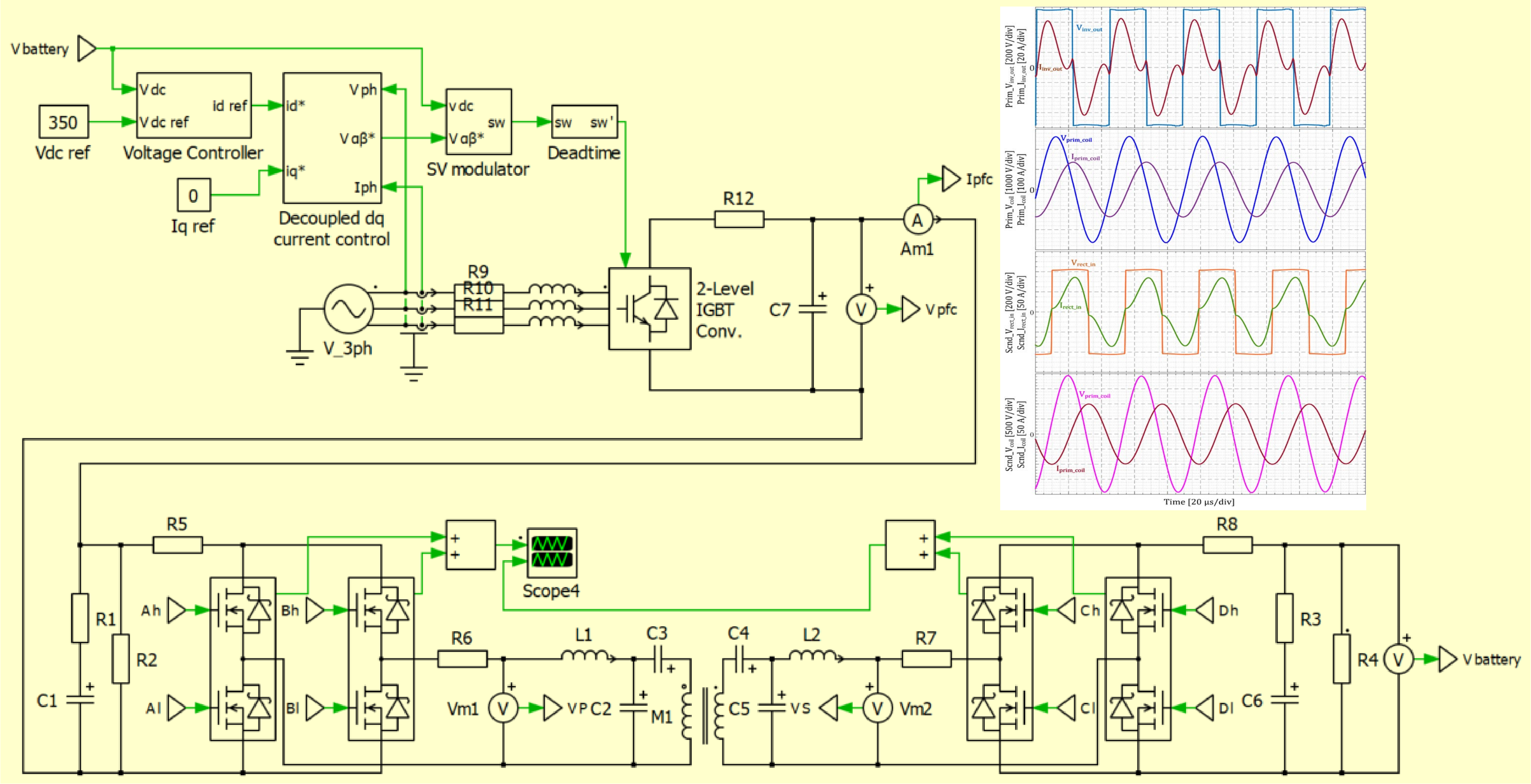
Experimental validation of the gain characteristics



Experimental data

Technical Accomplishments – BP II

Entire system simulations with closed loop control: Charging and discharging



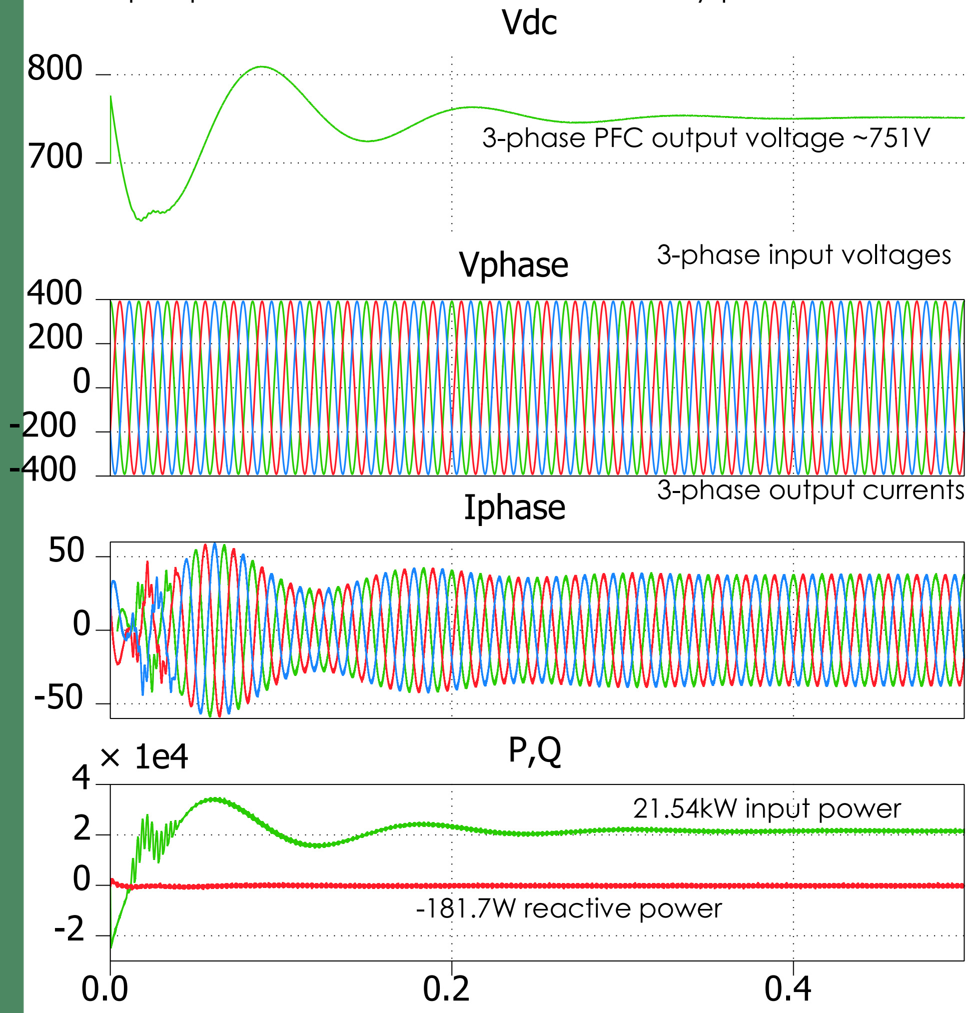
Simulation model of the entire system

Battery voltage 350V,
Input voltage 480V 3-ph
Primary dc bus: ~750V
HF inverter switching frequency 22.5kHz

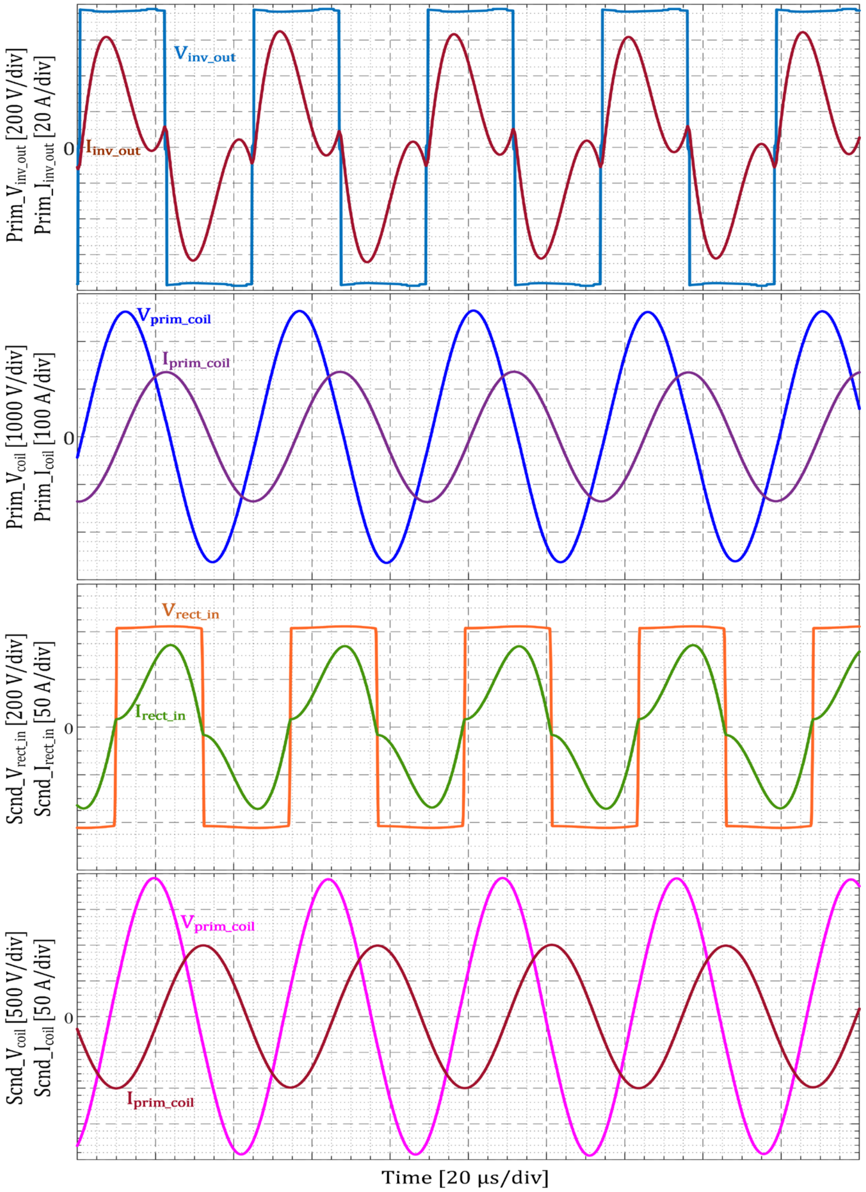
Technical Accomplishments – BP II

Entire system simulations with closed loop control: Charging

Input currents: 26A$_{rms}$, Input current THD: ~1%
Input power factor: 0.999, 20kW battery power

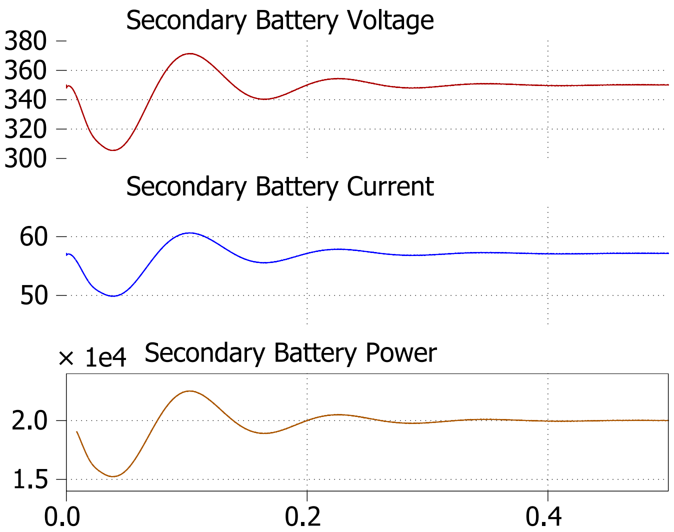


Grid-side measurements for charging mode



Resonant stage measurements for charging mode

Complete system model with full functionality in both power flow directions that validates the design and provides confidence for the hardware operation.

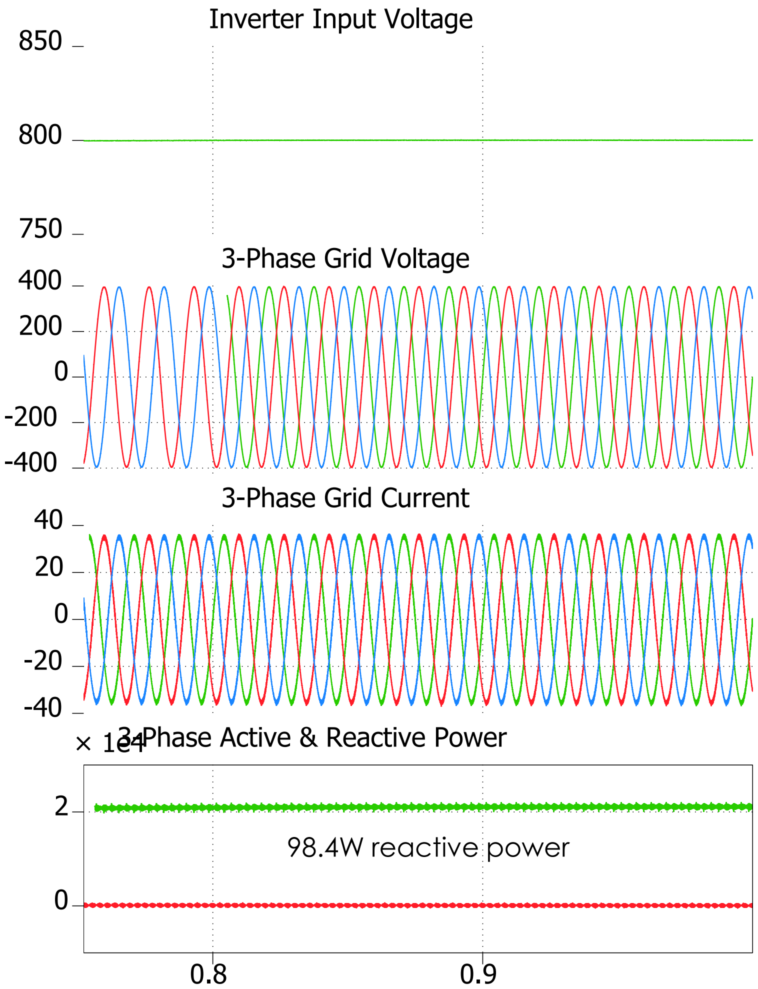


Vehicle-side measurements for charging mode

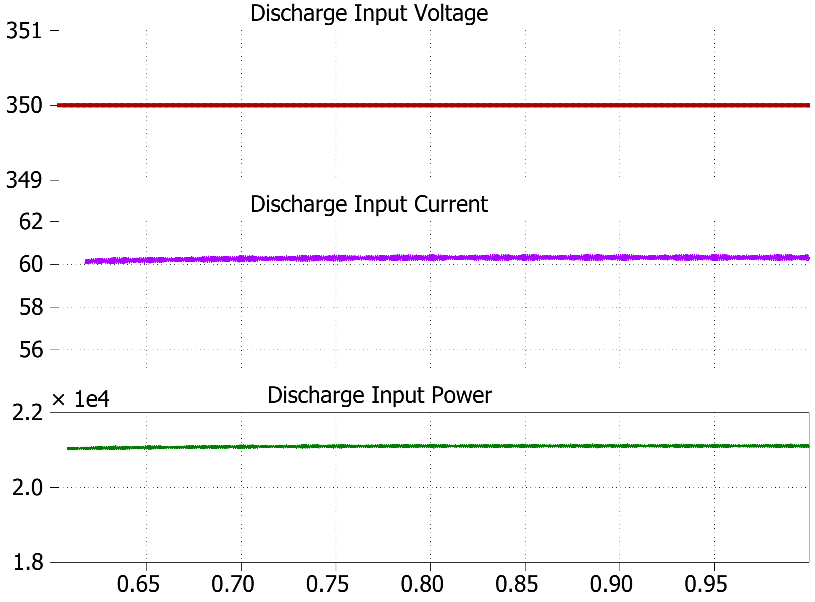
Technical Accomplishments – BP II

Entire system simulations with closed loop control: Discharging

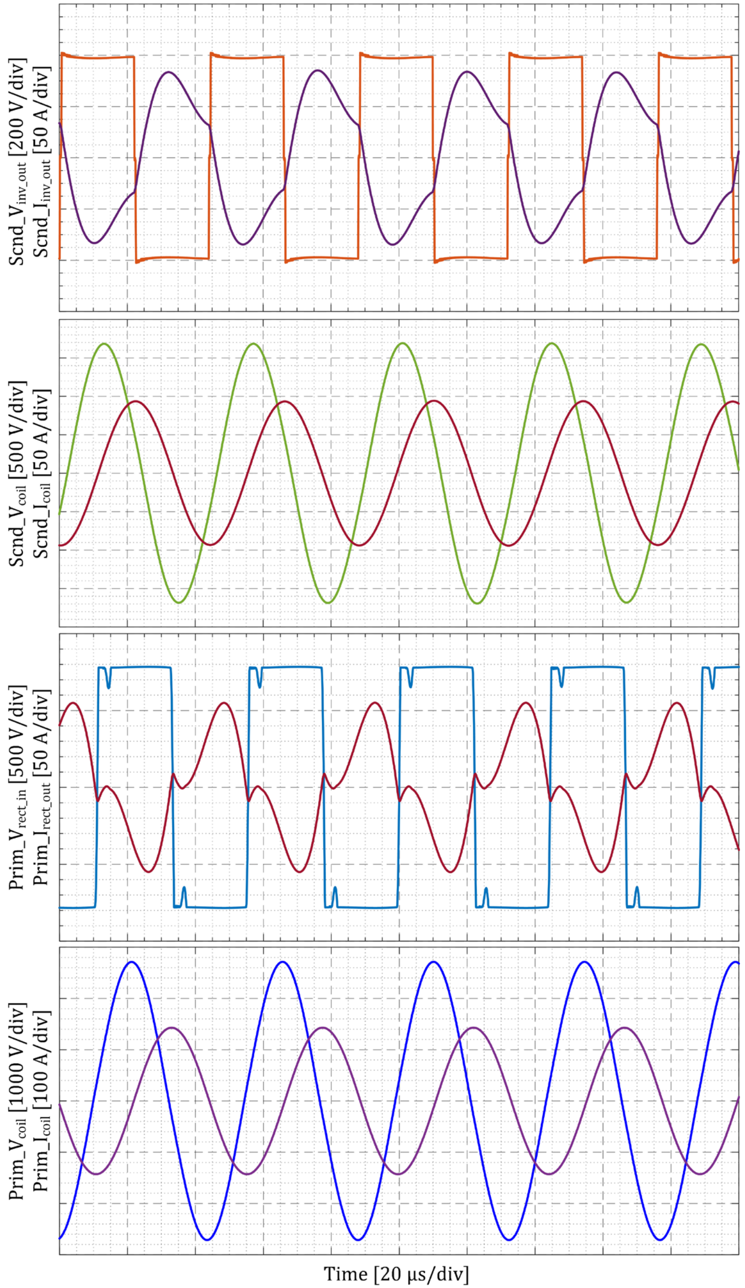
Grid currents: 25A_{rms}, Grid current THD: ~1%
Grid power factor: 0.999, ~21.5kW battery power, ~20 kW grid power



Grid-side measurements for discharging mode



Vehicle-side measurements for discharging mode



Resonant stage measurements for discharging mode

Technical Accomplishments – BP II

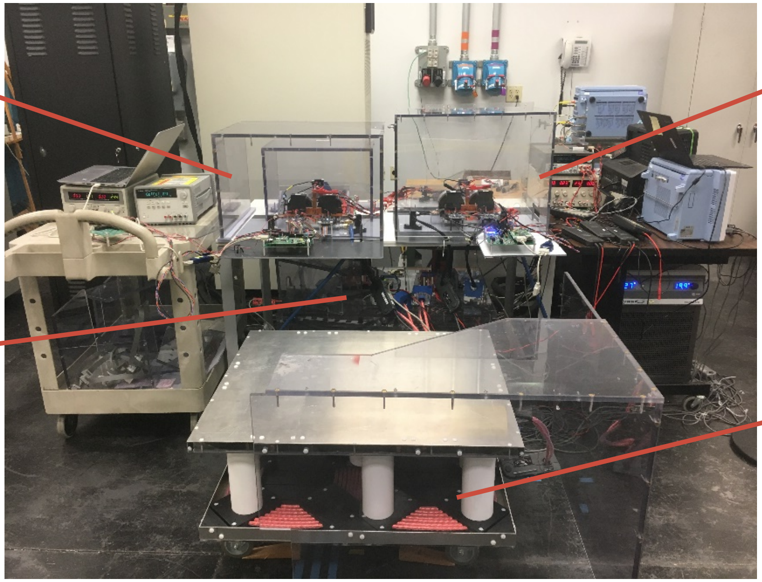
Experimental test setup and results of the resonant stage (dc-to-dc)

Secondary-side hardware

Primary-side hardware

LCC-LCC tuning components

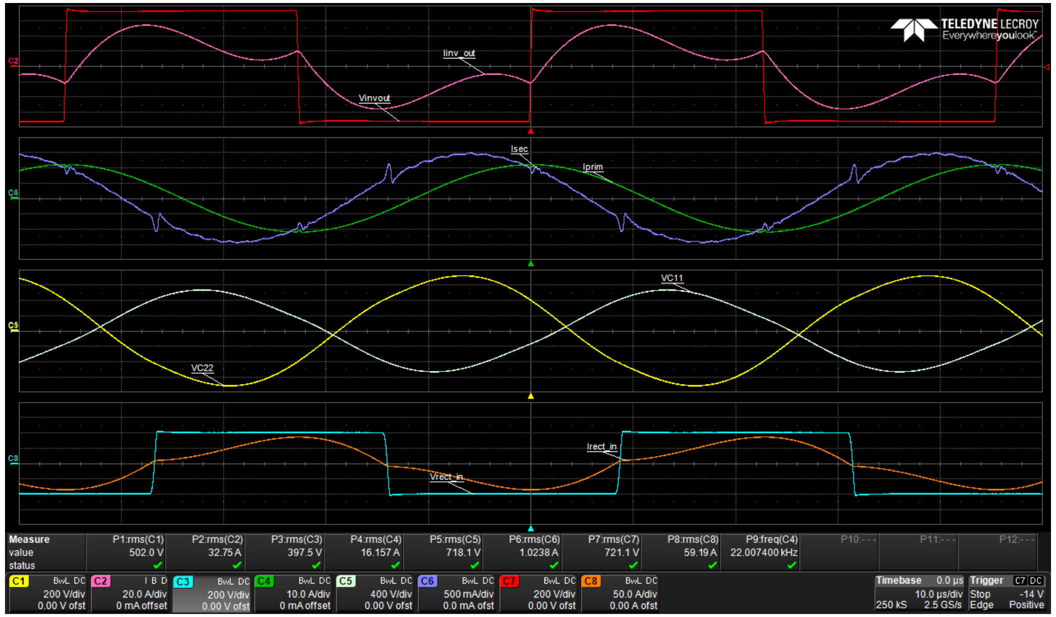
Coupling coils with 11” airgap



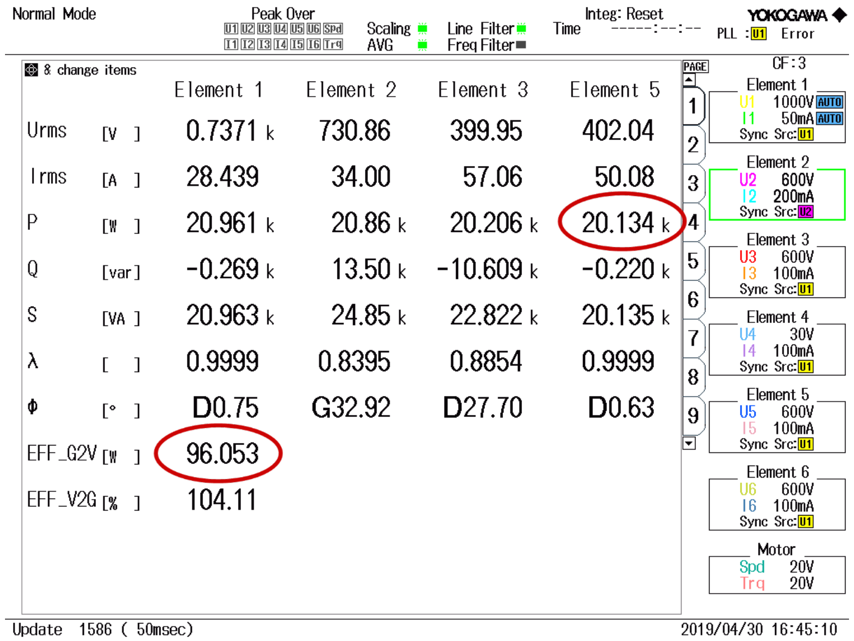
Experimental test setup

- **~20kW** power delivery to the battery emulator
- Grid-to-vehicle power flow
- ~737V_{in_dc}
- ~400V_{out_dc}
- ***96%*** dc-to-dc efficiency
- Inverter, rectifier, coils, primary and secondary-side LCC tuning components

- Zero-voltage-switching (ZVS) operation



Operational waveforms for charging mode



Normal Mode | Peak Over | Scaling AVG | Line Filter Freq Filter | Integ: Reset | YOKOGAWA | PLL : U1 Error

8 change items

		Element 1	Element 2	Element 3	Element 5
Urms	[V]	0.7371 k	730.86	399.95	402.04
Irms	[A]	28.439	34.00	57.06	50.08
P	[W]	20.961 k	20.86 k	20.206 k	20.134 k
Q	[var]	-0.269 k	13.50 k	-10.609 k	-0.220 k
S	[VA]	20.963 k	24.85 k	22.822 k	20.135 k
λ	[ ]	0.9999	0.8395	0.8854	0.9999
φ	[°]	D0.75	G32.92	D27.70	D0.63
EFF_G2V	[W]	96.053			
EFF_V2G	[%]	104.11			

CF:3
Element 1 U1 1000V AUTO I1 50mA AUTO Sync Src: U1
Element 2 U2 600V I2 200mA Sync Src: U2
Element 3 U3 600V I3 100mA Sync Src: U1
Element 4 U4 30V I4 100mA Sync Src: U1
Element 5 U5 600V I5 100mA Sync Src: U1
Element 6 U6 600V I6 100mA Sync Src: U1
Motor Spd 20V Trq 20V

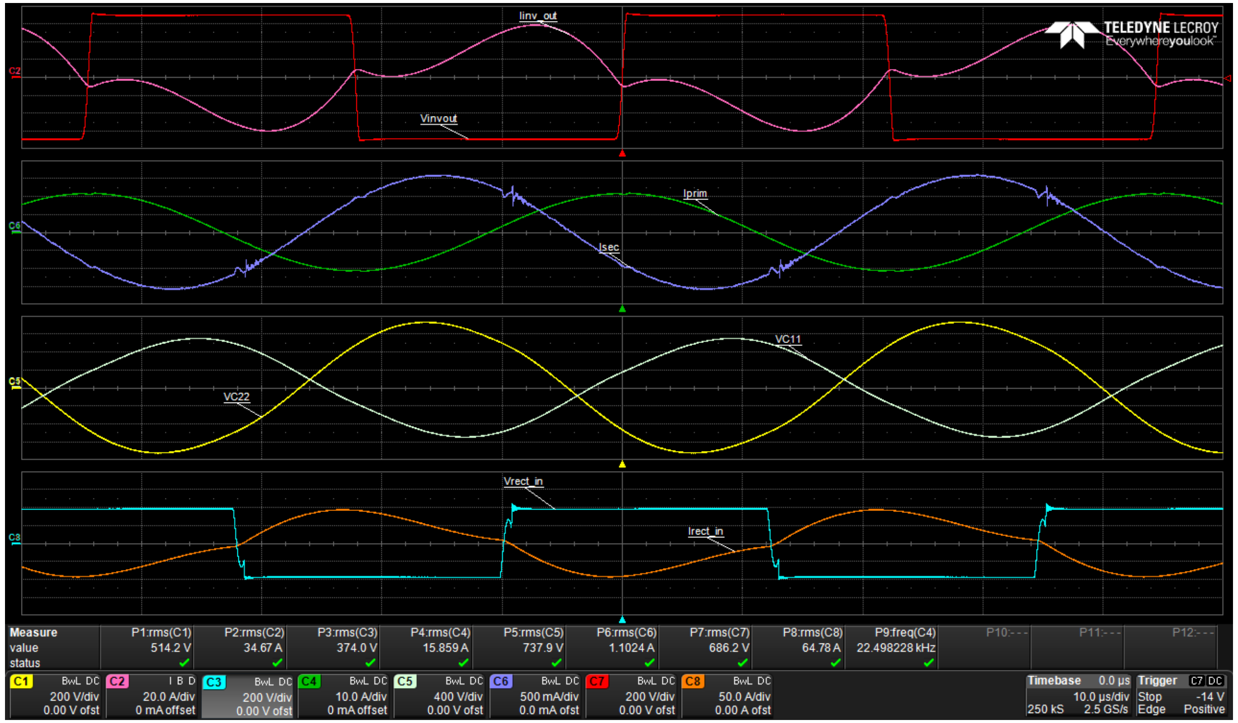
Update 1586 (50msec) 2019/04/30 16:45:10

Power analyzer screenshot for charging mode test results

Technical Accomplishments – BP II

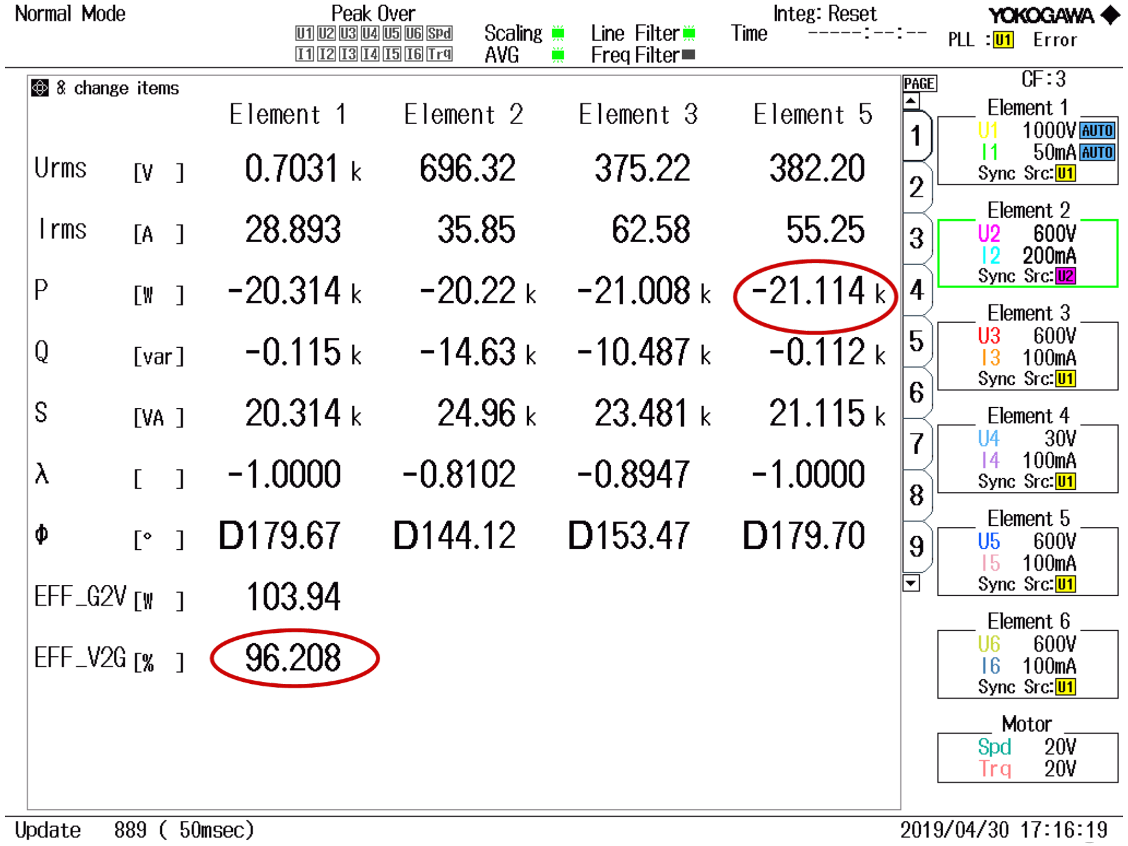
Experimental test setup and results of the resonant stage

- Zero-voltage-switching operation both on primary and secondary power converters



Operational waveforms for discharging mode

- **~21kW** power delivery from battery emulator to the input dc bus
- Vehicle-to-grid power flow
- ~700V$_{prim_dc}$
- ~382V$_{batt}$
- **96.2%** dc-to-dc efficiency
- Inverter, rectifier, coils, primary and secondary-side LCC tuning components

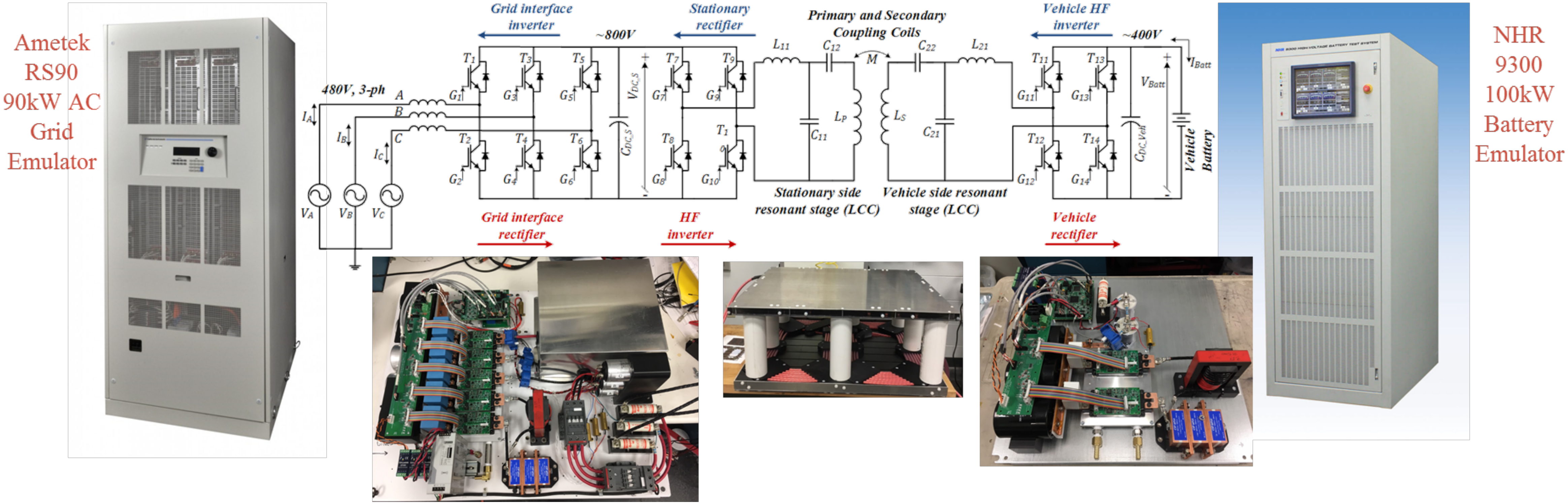


Power analyzer screenshot for discharging mode test results

Technical Accomplishments – BP II

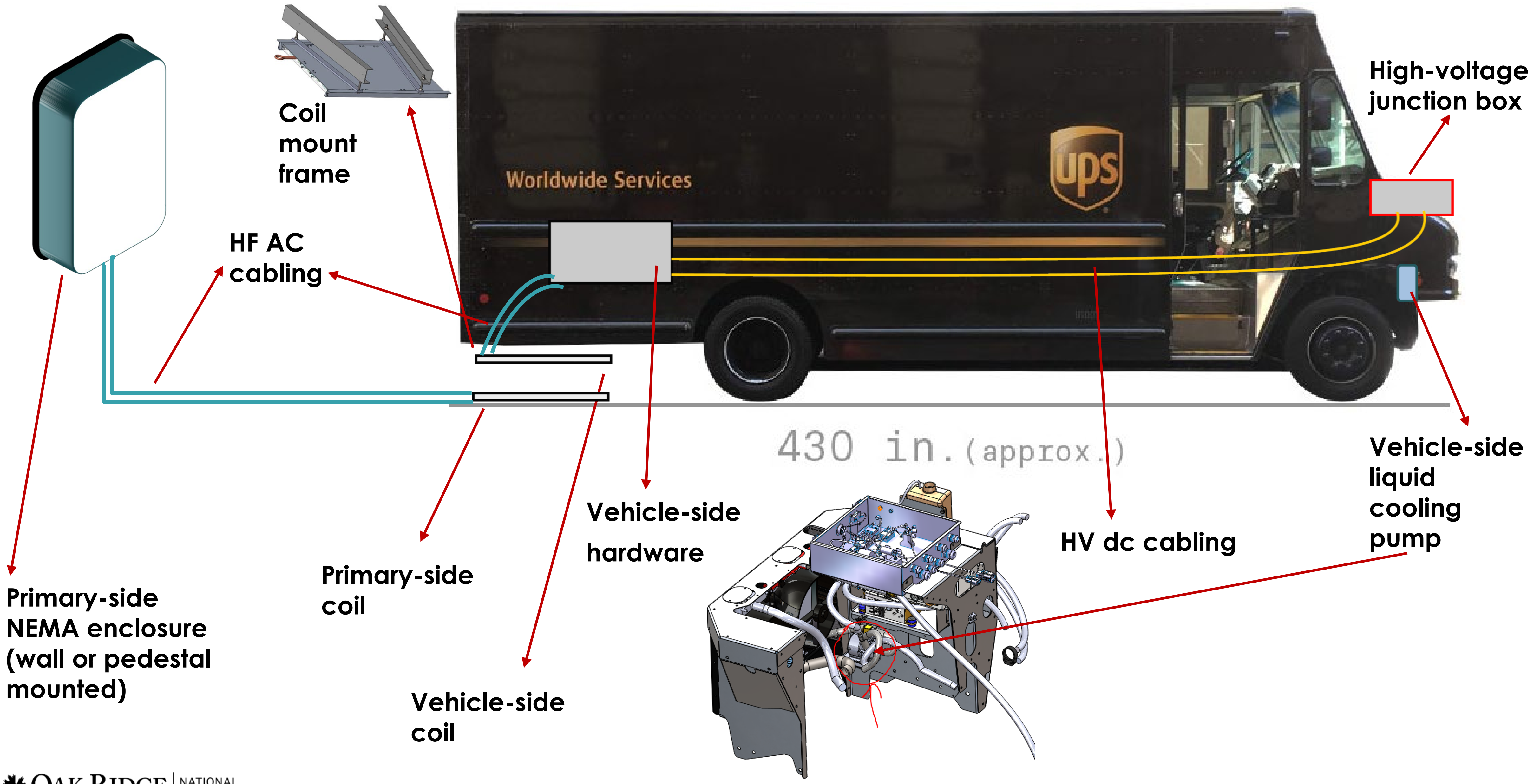
Benchtop test setup and validation of power conversion stages and the system as a whole

- Each power conversion stage is tested and validated parameters and functionalities (both component and subsystem level)
- Whole system integrated together
- Both power flow directions
- Communications link with closed loop operation



Benchtop setup diagram

Vehicle Integration Efforts – BP II



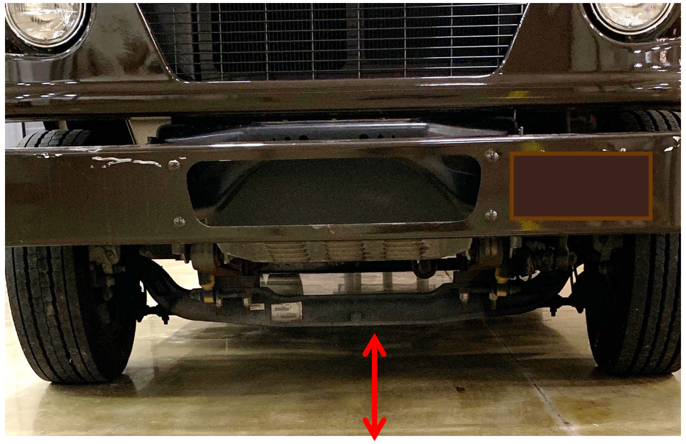
Vehicle Integration Efforts – BP II

UPS plug-in hybrid electric truck at ORNL's GRID-C

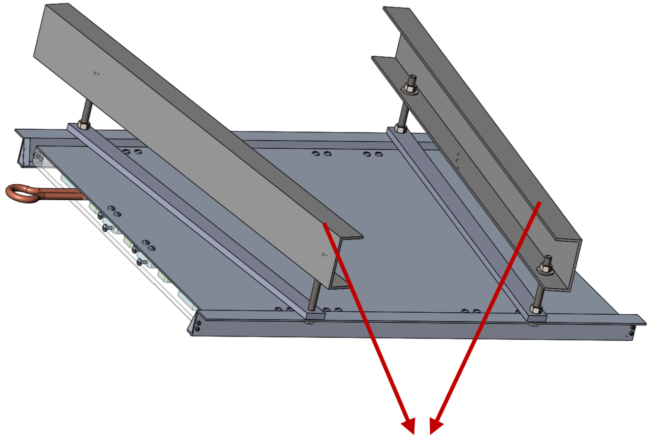
Vehicle Integration Efforts – BP II

February 27th, 2020 Demonstration day

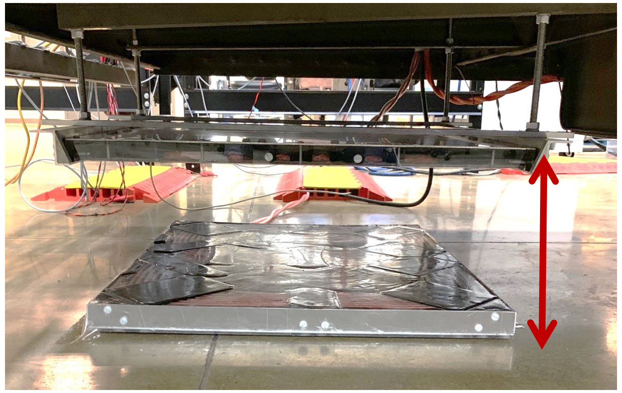
Vehicle Integration Efforts – BP II



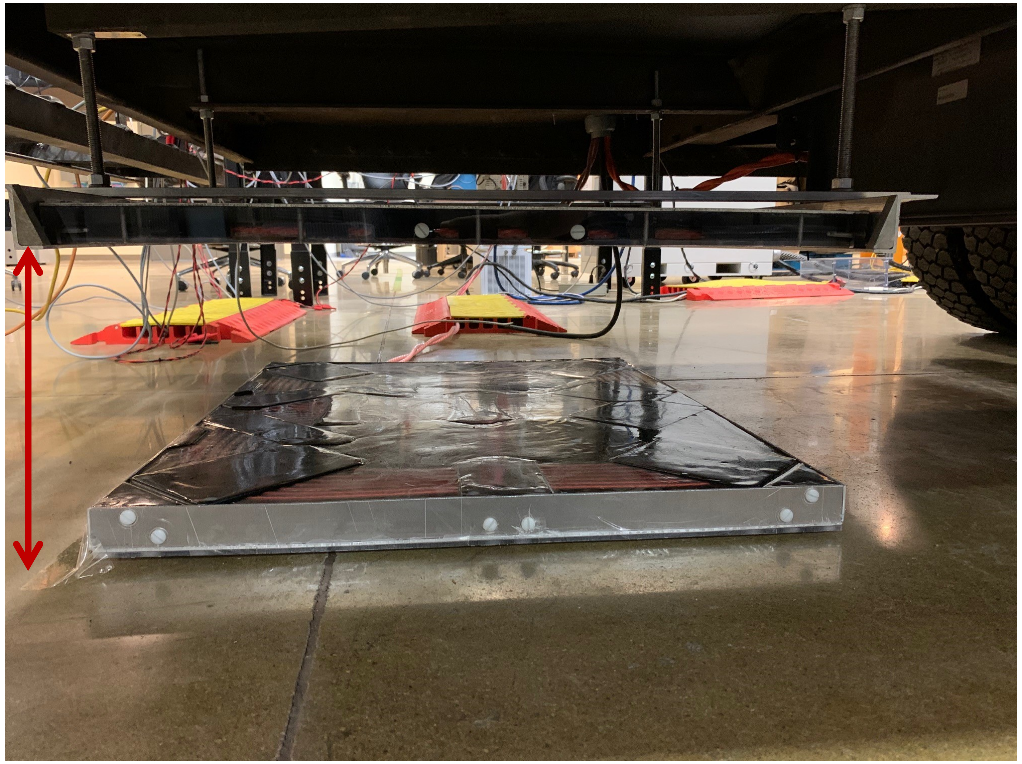
8" – minimum ground clearance, lowest point under the vehicle (coupling rod)



Mounts on the vehicle rails

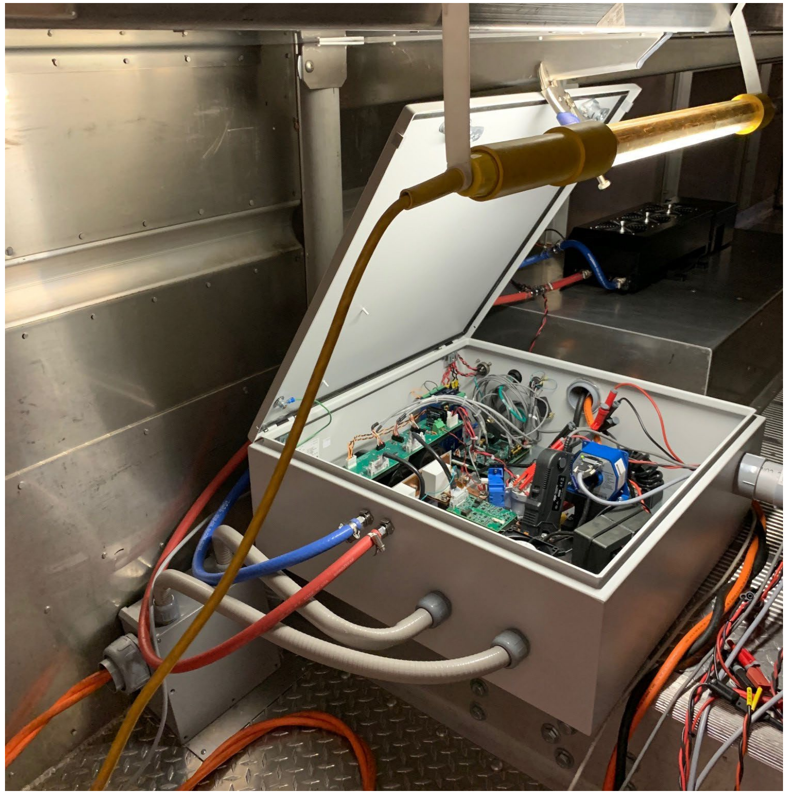


11" magnetic airgap, surface from secondary coil to the ground level

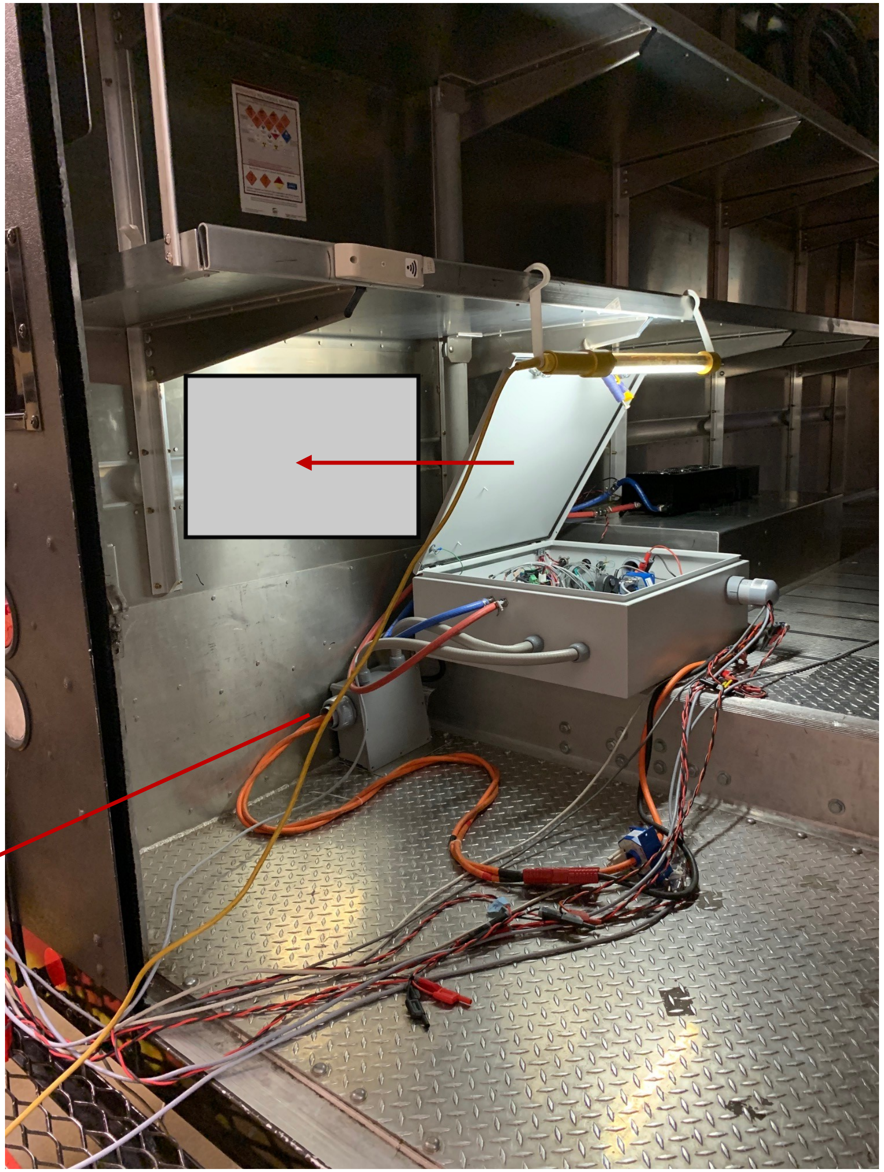


- Coil mounting rail frames
- Adjustable height
- ORNL design
- Fabricated in ORNL machine shop

Vehicle Integration Efforts – BP II

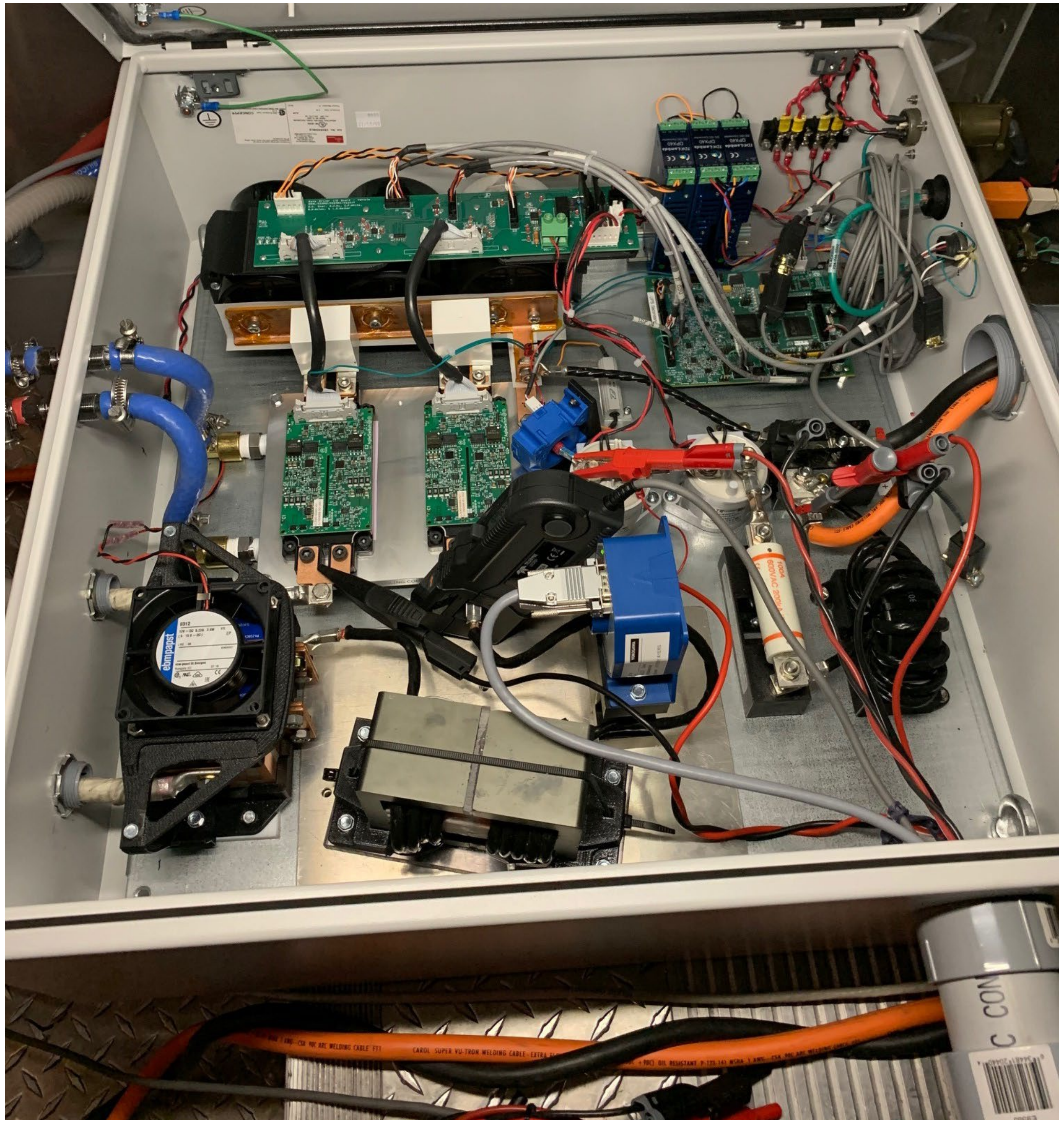


Vehicle-side hardware and HF ac and dc connections



Vehicle-side junction box, passage for HF ac and HV dc wiring

Vehicle Integration Efforts – BP II

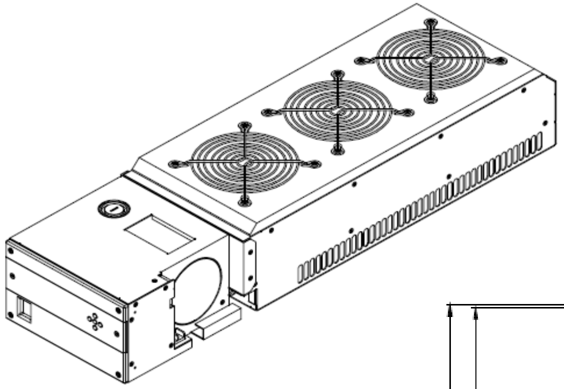


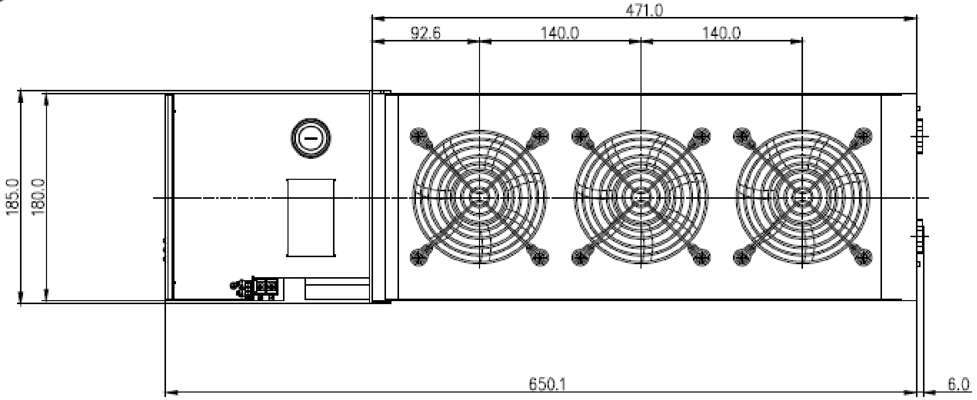
Detailed view of the vehicle-side hardware

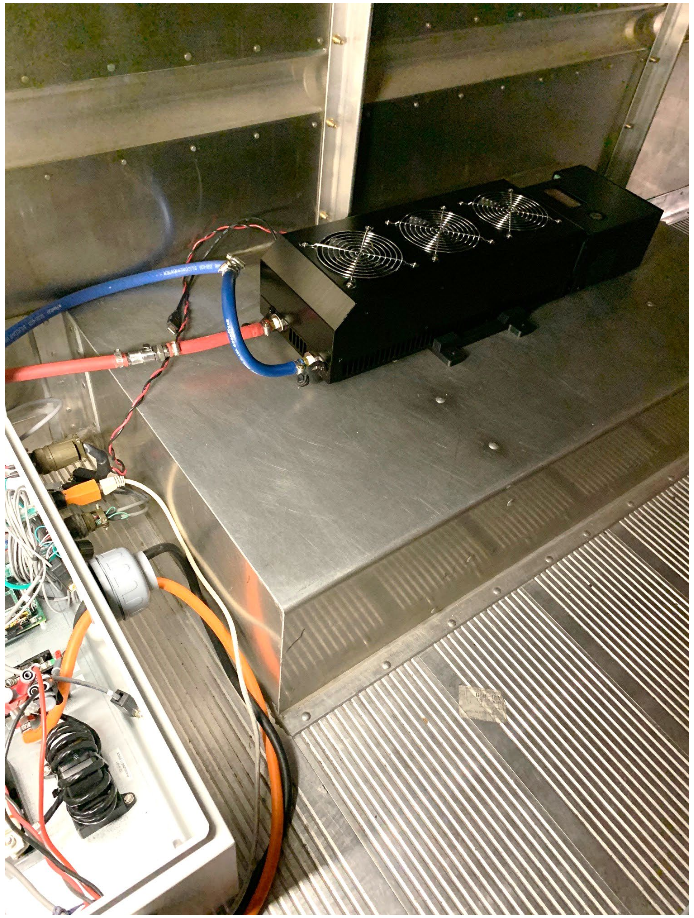
- Slightly larger than the vehicle's EDN EVO 11kW on-board charger
- EDN EVO: 90% efficient
- ORNL WPT: ~92% in charging (vehicle side is about ~99% efficient)
- Bi-directional rectifier/inverter

Vehicle Integration Efforts – BP II

- Using vehicle-side pump would have significant pressure drop and temperature drift
- Had to integrate a chiller nearby the secondary hardware
- 12V operated, ~5A, ~60W consumption (vehicle-side hardware requires another ~30W from the 12V bus)
- Very compact, low profile chiller







Vehicle-side liquid cooling system integration

OAK RIDGE National Laboratory | NATIONAL TRANSPORTATION RESEARCH CENTER

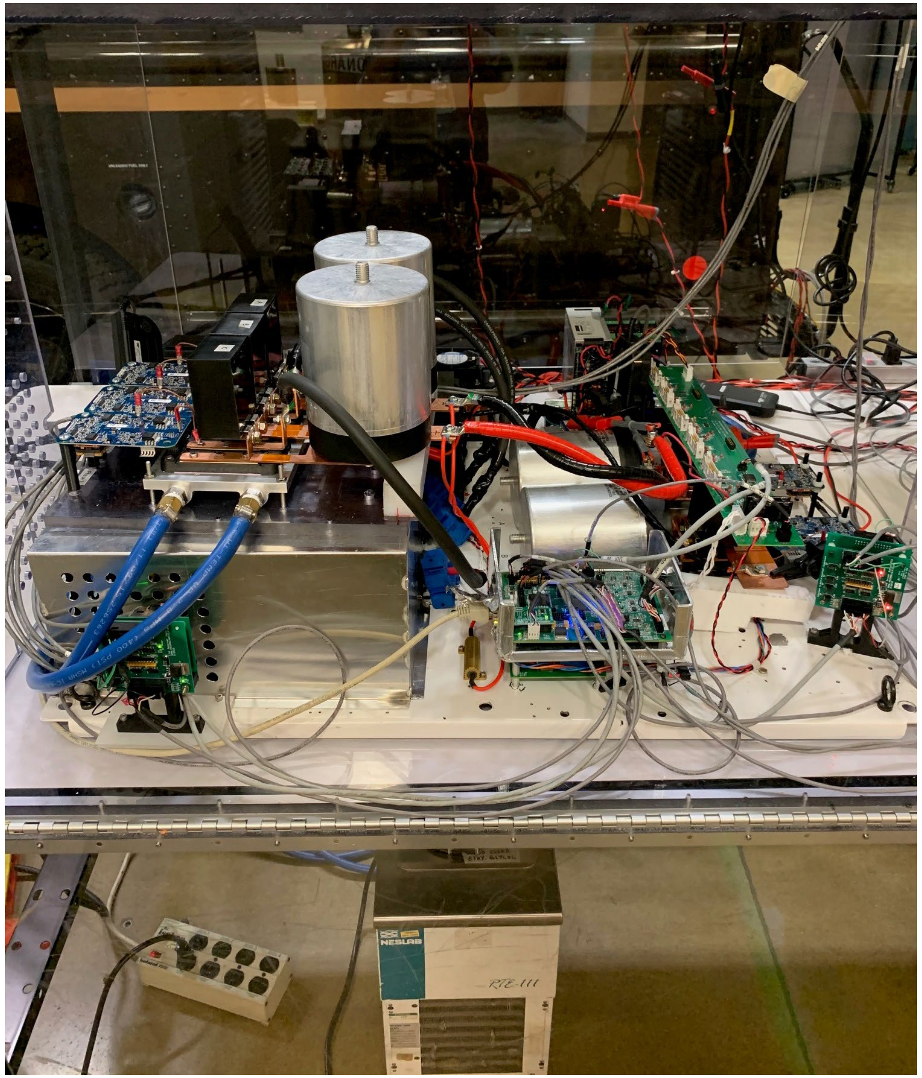
Primary-Side Hardware and System Instrumentation

- 480V, 3-phase connection

(277V phase-to-neutral, 480V phase-to-phase)

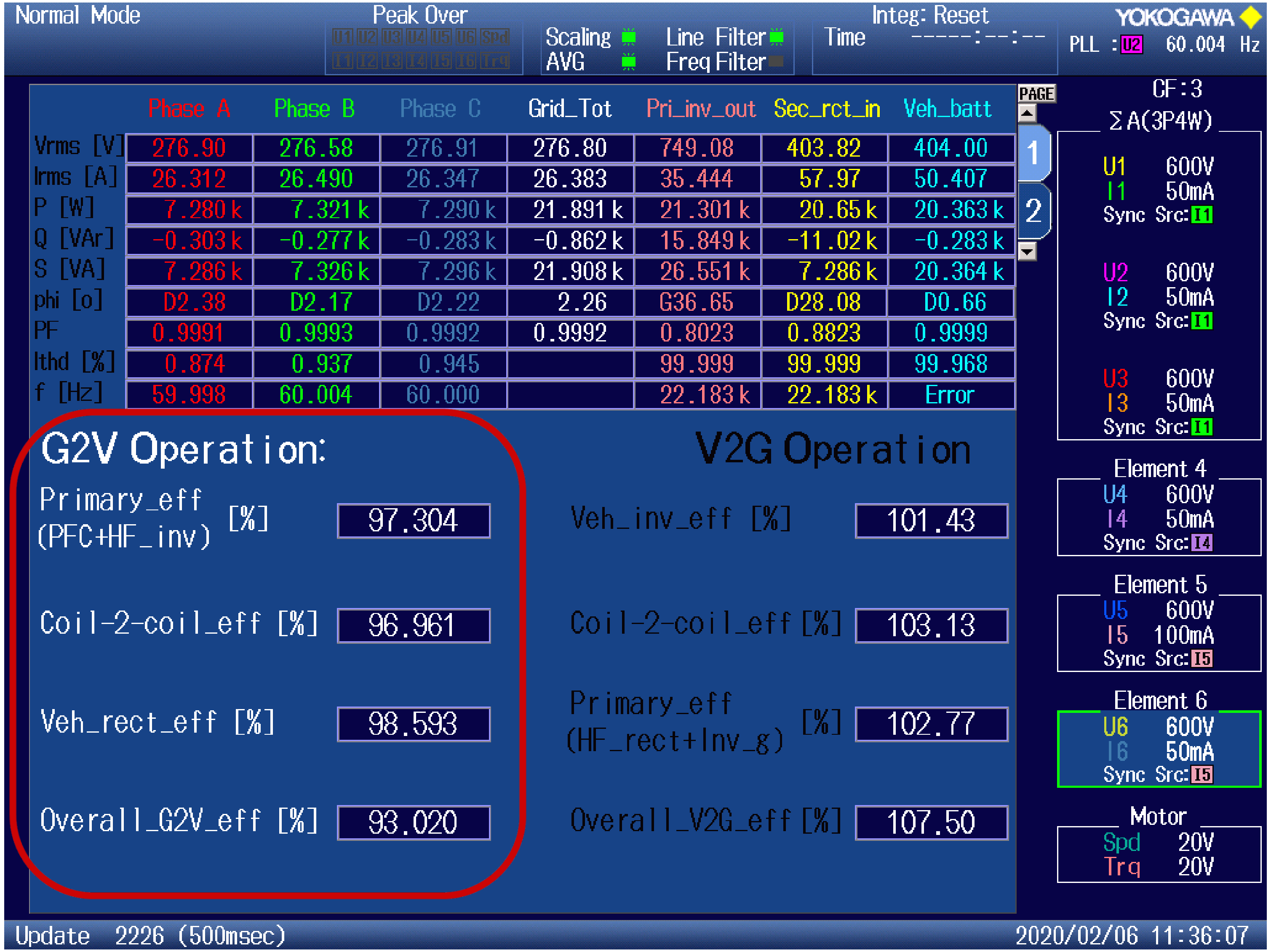
- HF output cable feeding the transmit coil
- Liquid cooled

Instrumentation of the BWPT system for functionality and performance demonstration



Primary-side grid-connected hardware with output to the primary coupler

End of BP-II: Demonstration of the BWPT System – Charging Mode

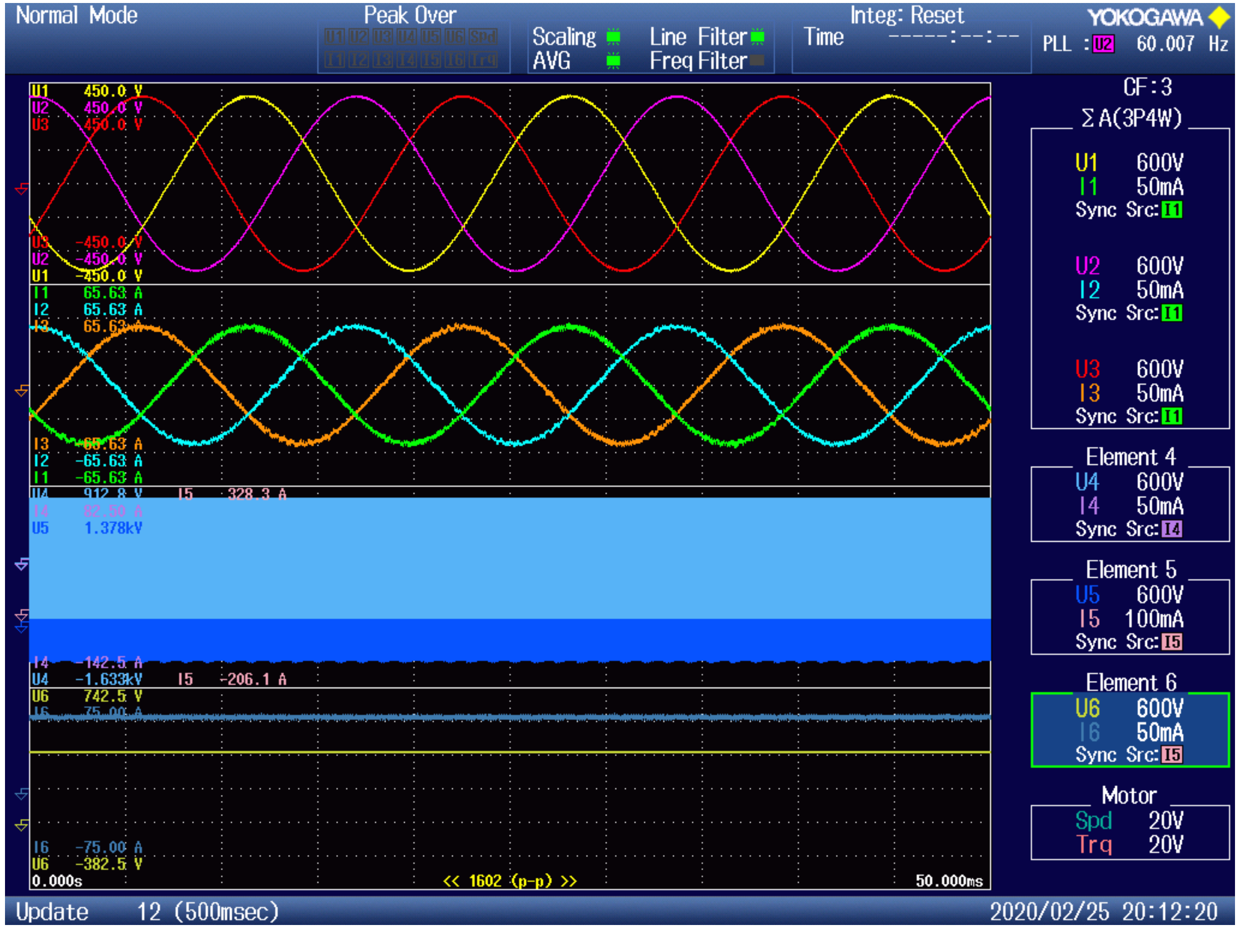


Power analyzer test results for the charge mode of operation

- Power analyzer for stage-by-stage power flow and efficiency of the system

- **20.36 kW** to the vehicle battery
- **93%** efficiency
- Power factor: **0.999**
- ITHD on the grid side: **0.7-1%**

End of BP-II: Demonstration of the BWPT System – Charging Mode



3-phase grid voltages and currents for the charge mode of operation

Primary-side HF inverter output and vehicle-side rectifier input voltages and currents for the charge mode of operation

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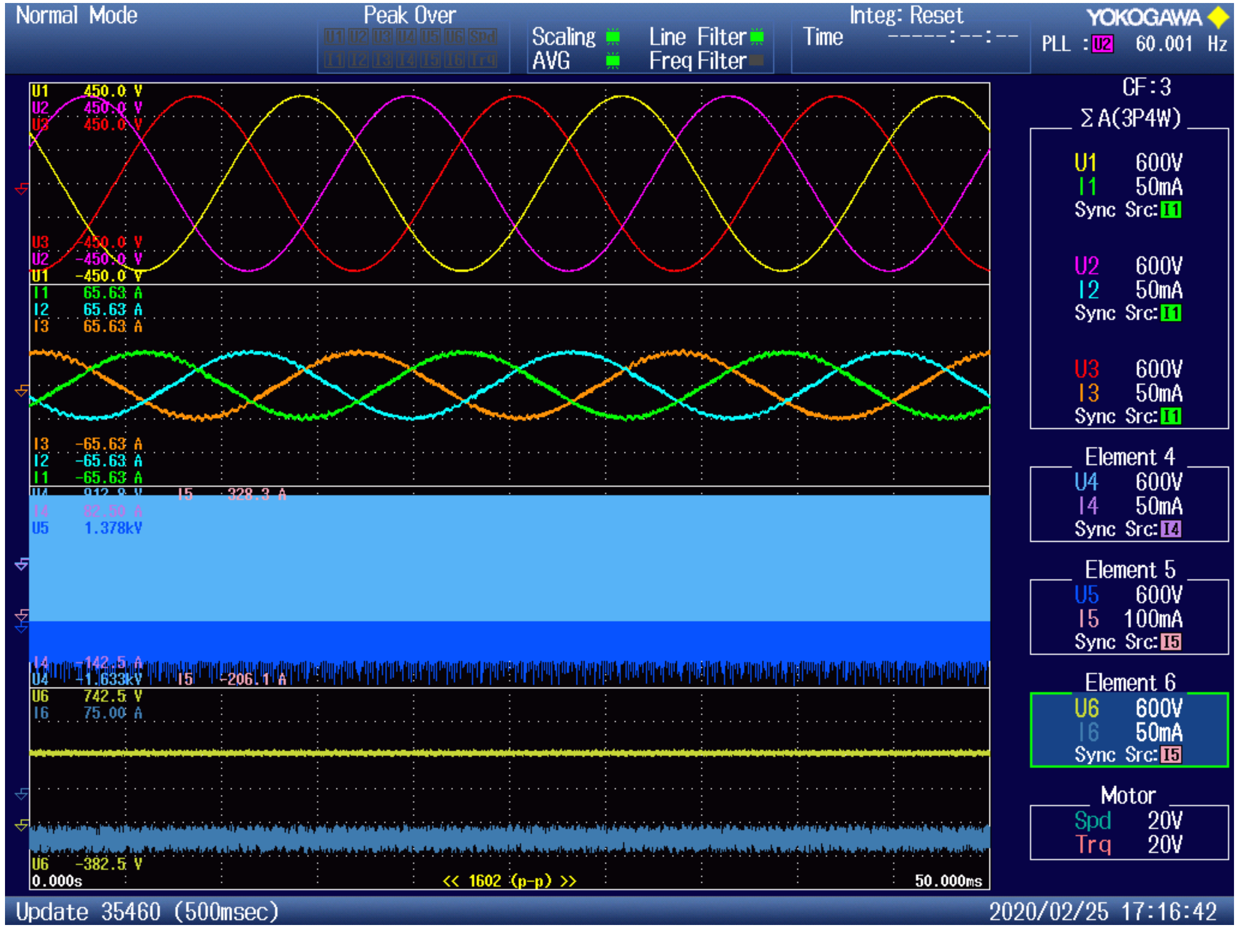
End of BP-II: Demonstration of the BWPT System – Discharging Mode

Power analyzer test results for the discharge mode of operation

- Power analyzer for stage-by-stage power flow and efficiency of the system in discharging operating mode
- **12.8 kW** to 480V power grid
- **89.1%** efficiency
- Power factor: **0.997**
- ITHD on the grid side: **1-1.6%**

End of BP-II: Demonstration of the BWPT System – Discharging Mode



3-phase grid voltages and currents for the discharge mode of operation (note the 180 degrees of phase-difference between voltages and currents)

Vehicle-side inverter output and primary-side HF rectifier input voltages and currents for the discharge mode of operation (note the 180 degrees of phase-difference between voltages and currents)

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End of BP-II: Demonstration of the BWPT System – Discharging Mode

Power analyzer test results for the discharge mode of operation

- Additional data point with ~7.2 kW back to the grid
- 86.67% overall efficiency from vehicle battery to the grid connection

Response to Previous Year Reviewers' Comments

- Project team would like to thank all of the reviewers for the feedback and the comments.
- Some comments:
  - *The reviewer remarked the approach for the research has been excellent. The team has achieved a very high efficiency for a significant gap of 11 inches. The team is providing a comprehensive, end-to-end solution, which is very unique to this project.*
  - *The reviewer commented that the project had a well thought-out approach to address the barriers of wireless power transfer with large air gap, at a high power level, and with bidirectional power flow.*
  - *The reviewer remarked the team has reported a 96% DC-to-DC efficiency with a gap of 11 inches. This is a very impressive result.*
  - *A very detailed discussion was presented of the build and testing of the design to achieve and exceed the efficiency goals.*
  - *The reviewer remarked the proposed future research is sound and natural. The reviewer is eager to see the system tested and evaluated with a real medium-duty truck.*
  - *The reviewer remarked the project is highly relevant to DOE. It addresses a key feature that will be required by EVs to be successful in the market.*
  - *The reviewer said the project has a good chance in creating a commercial product enabling efficient and cost-effective wireless charging for EVs. This work directly and solidly addressed the overall DOE goal on reducing the barriers in vehicle electrification, wireless charging, and V2G integration for improved V2G operations.*
  - *The reviewer said the presenter made it clear that the team has sufficient resources. The reviewer sees no reason to question that except to ask who will be the demo data analysis team.*

Response to Previous Year Reviewers' Comments

- One common question/comment from reviewers were that the ORNL is significantly leading all the aspects of the project and collaboration and the role of the other partners were somewhat limited.
  - CALSTART is the lead organization managing the project and also working on the business case analysis of the bi-directional charging systems
  - ORNL closely collaborated with Workhorse on the vehicle integration challenges and received substantial engineering support
  - ORNL also works closely with UPS for the site preparation and deployment aspects and received input on the use cases
  - Collaboration with Cisco is also an ongoing effort on the bi-directional wireless communication between the primary-side and the vehicle-side units
  - Cisco may also have an additional role on integrating the system into an energy management strategy that the UPS may implement in a future activity with ORNL's strong support

Collaboration and Coordination with Other Institutions

- **CALSTART**: Project lead, project management, budget management, reporting, overall coordination, V2G economic analysis, business case analysis
- **ORNL**: Technical lead, system design, development, integration, testing, deployment
- **UPS**: End-user, deployment site, integration coordination
- **Workhorse**: Vehicle manufacturer, vehicle systems integration and engineering support
- **Cisco**: Developed and provides communication interfaces from energy management system to the BWPT system and also the vehicle to grid / grid to vehicle communications

Remaining Challenges and Barriers

- Site preparation and final deployment at the SMART hub at the UPS' Sandy Creek facility

- The electric and electromagnetic field emissions should be less than the limit levels set by the ICNIRP 2010 guidelines inside and around the vehicle while transferring 20kW across 11 inches airgap. Team started measurements and no issues observed so far

- Team needs to perform more long-term operation tests (up to 3 hours continuously) to ensure both the primary and secondary thermal management systems will function sufficiently without significant parameter draft

- While the team is practicing constant current charging/discharging, a more "smart charge management" system might be integrated in future to follow a given charge profile

Any proposed future work is subject to change based on funding levels

Proposed Future Research

- **BP III (remainder of FY20 and a portion of FY21)**
  - Final deployment, validation, testing at the demonstration site and data collection for long term operation.
  - Business case analysis of bi-directional charging systems

Any proposed future work is subject to change based on funding levels

Summary

- **Relevance**: Increase the benefits and reduce the barriers in vehicle electrification, wireless charging, and vehicle to grid integration for improved V2G operations
- **Approach**: Proposed a bi-directional wireless power transfer system that operates at a high airgap for medium duty delivery trucks with high-efficiency and functionality through advanced power electronics and magnetics design, vehicle systems integration, and control system design
- **Technical Accomplishments**:
  - Designed and developed all the system power conversion stages including all the subsystems and components
  - Currently testing the whole system together for validations and functionalities
- **Collaborations and Coordination with Other Institutions**:
  - **CALSTART**: Project lead and project management
  - **UPS**: Test vehicle provider, end-user, final deployment site
  - **Workhorse**: Plug-in hybrid and electric delivery truck manufacturer, engineering support on vehicle integration
  - **Cisco**: Providing radio communication systems for commanding the system and to form feedback control loops
- **Future Work**:
  - Final deployment, validation, testing at the demonstration site and data collection for long term operation

Any proposed future work is subject to change based on funding levels